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Color Discrimination Characteristics Depending on the Background Color in the (*L*, *M*) Plane of a Cone Space

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We investigated color discriminability on the background color. The measurement was carried out at over 21 background colors in (*L*, *M*) plane of a cone space by four observers. We used low temporal stimulus frequency (1 Hz) so that threshold was determined by the red-green opponent mechanism. Results showed that color discriminability depends on the background colors. Threshold was higher with a more saturated background color. This suggests that the sensitivity of the red-green opponent mechanism is high when the mechanism's output is small and increases with the output levels of the mechanism. To confirm this relationship between the red-green mechanism and color discriminability, color appearance depending the background color was also evaluated. There was a strong correlation between the sensitivity and the perceived whiteness. Both sensitivity and whiteness value were highest at around the equal energy white point and decreased with increase in the difference between background color and equal energy white. This suggests that the adaptation state of the red-green opponent color controls color discrimination.

Key words: color discrimination threshold, background color adaptation, red-green opponent mechanism, color appearance, whiteness

1. Introduction

Color discrimination is one of the most important factors in human color vision. Color discrimination thresholds provide information of response properties of cones and chromatic channels. They are also useful to estimate visible color differences like in paints of cars or in fabric colors. Unfortunately, however, we cannot use a single number to indicate the visible difference in color for the use. Color discriminability depends on the experimental conditions such as spatiotemporal characteristics, background colors for adaptation[1–7)] as well as the stimulus color itself.[5,6)] It is necessary to take into account these factors to evaluate color differences for general purposes. The factors influence color discriminability are also important to investigate the response properties of the mechanisms related to color vision.

Two earliest investigations of the color discriminability depending on the stimulus color were carried out by Wright[5)] and MacAdam.[6)] They found that discrimination thresholds plotted on the CIE *xy* color diagram differed among different test colors. This implies that the same distances at different locations on the (*x*, *y*) color diagram do not correspond to the same perceptual color difference. Ever since, several researchers have tried to interpret the results based on responses of cones and opponent color processes. Among them, recent studies suggested that nonlinear responses of color opponent processes predict the dependency of color discriminability on stimulus colors. For example, Boynton *et al.*[7)] analyzed the MacAdam's color discrimination data, assuming three color mechanisms and showed that threshold to detect the color difference increases with the increase in response of a color opponent channel. This shows the similarity to the fact that luminance incremental thresholds can be expressed by a constant Weber ratio, which suggests a logarithmic-like nonlinear response function of the mechanism concerned. Nonlinear responses in color vision are often reported Shioiri *et al.*[8)] and Smith *et al.*[2)] related nonlinear responses to color discrimination threshold. Smith *et al.*[2)] measured discrimination threshold as a function of the L-M values of test stimulus (test color varied along the color direction of L-M with a fixed luminance) and proposed a model of the mechanism to discriminate color, showing that the model can predict their results using physiologically plausible parameters. Most of experimental results in the literature consistent with the presumption that the two opponent color mechanisms and the luminance mechanism contribute to color discriminability. Assuming sensitivity of each mechanism and the manner of interactions (*e.g.*, probability summation[9)]) predict the color discrimination thresholds of different test colors.

The effect of background color on color discriminability is one of the important factors which need more investigation. Background colors influence appearance of colors strongly as chromatic adaptation, color contrast, and color assimilation indicates. If the opponent color mechanisms determine the color discrimination threshold, their adaptation states should also influence the threshold. When we consider color vision under various types of illumination light for example, we should investigate how the color, or spectral distribution, of illumination influences color discriminability. Therefore, it is important to consider the effect of background colors in addition to the test color itself. In this report, we focused on color discrimination characteristics depending on the background color and the color appearance under the same background adaptation. We measured color discrimination thresholds using more than 21 colors with a large adaptation field of the same color, which were distributed evenly on the (*L*, *M*) plane in the cone response space. This is not to intend to isolate adaptation effect from the effect of the test color itself. Rather we used this condition to investigate the both of the effect considering the color analysis. The test color under these conditions corresponds to the white paper under the

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illumination with these color coordinates of the background colors. To investigate the relationship between color discriminability and adaptation states of the red-green color opponent mechanism due to the surrounding color (background color), we also estimated color appearance of the test color with a color naming procedure.

2. Experiment

We carried out two different experiments. One was threshold measurement experiment and the other was color naming experiment.

2.1 Apparatus

The stimuli were generated on a color monitor (SONY GDM-17SE2T) driven by a video board (Cambridge Research Systems VSG 2/4) under the control of a personal computer. This system had 640 by 480 pixels spatial resolution and 120 Hz frame rate with 15 bits luminance resolution for each phosphor. Each phosphor output was calibrated with a spectroradiometer (Minolta CS-1000) and photometer (Cambridge Research Systems OptiCAL).

2.2 Stimuli

The spatial arrangement of the stimulus was shown in Fig. 1. The test field was at the center of a 6-deg square background and consisted of a two by two array of four 1-deg squares with 0.1-deg black separations. Color of either of the four squares changed on each trial as a test stimulus. The position of the test square was randomly chosen from trial to trial and the observer was asked to find the square which the observer saw the change in the color discrimination experiment. The squares were separated to reduce the influence of high spatial frequency components at the border between the background and test colors. Luminance contrast at the border would activate the luminance mechanism and threshold would be determined mainly by the luminance mechanism. Since our interest was in color opponent mechanisms, we placed the separation to minimize the influence of the luminance. The contrast of the test stimulus was changed temporally by a Gabor profile with 1 Hz peak frequency and 1 s duration. Squares in the test field were filled with the background color before and after the test stimulus presentation and the background color was presented through the

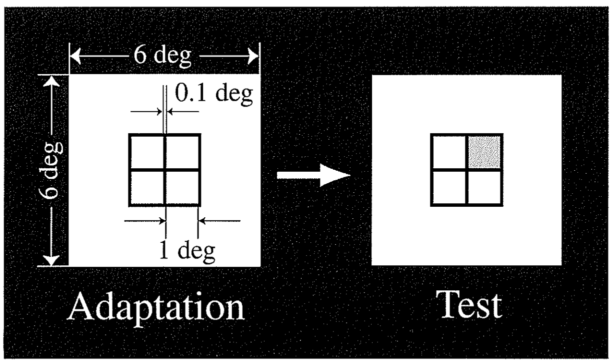

Fig. 1. The spatial arrangement of the stimulus.

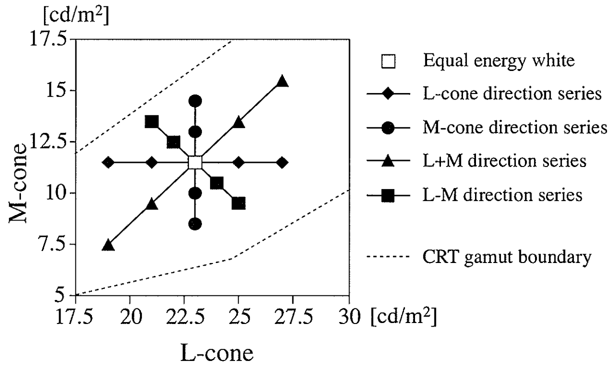

Fig. 2. The loci of background color in the (L, M) plane of the measurement.

measurement.

A cone excitation space with Smith and Pokorny's fundamentals[10] was used to represent stimulus colors and experimental results. Since the test was varied only L- and M-cone responses of test and adaptation colors in this study, all discrimination thresholds were described in the (L, M) plane of the space.

Twenty-one adaptation colors were initially selected in the measurement, which were placed along the five directions with the center of 34.5 cd/m^2 equal energy white. The adaptation color was shown in the (L, M) plane in Fig. 2. Five directions were L-cone direction (horizontal axis), M-cone directions (vertical axis), L+M direction (luminance direction), L−M direction (equal luminance direction), and S-cone direction. Five adaptation colors were set for each direction. After the measurements with all 21 adaptation colors, extra measurements were carried out with several additional adaptation colors near the equal energy white point to examine the details around the point.

The temporal modulation direction of the test stimuli was set in the (L, M) plane, which was expressed by a straight line passing through the origin. Each modulation direction included the change in both the red-green opponent and luminance components, except for L+M and L−M directions. We measured the threshold two opposite directions separately. When the modulated directions were opposite (i.e., 180 deg phase differences), the axis of modulation was the same as well as the peaks, but the direction of initial color change was in opposite. In the case of 0 degrees $(+L/-L)$ directions, the test stimulus changed first to reddish, then to greenish while the test stimulus changed first to greenish, then to reddish in the case of 180 deg $(-L/+L)$. The direction was set every 45 deg from 0 to 360 deg in the (L, M) plane, totaling eight modulation directions in the measurement.

2.3 Procedure

Before the trial start, observer adapted to the background color for three minutes. Test was presented at one of the four squares with the other three unchanged. The presentation duration was 1 second. A beep was presented at the beginning and the end of the test presentation. The observer responded which one of the four squares appeared differently by a keyboard. After the observer responded, the next trail started.

The test stimulus contrast changed following the observer's response by a typical, one-up-one-down staircase procedure. Feedback for the response was given by a beep after each response to keep observer's attention.

Color appearance evaluation was carried out with keeping the adaptation to the background color. The observer evaluated the color appearance of the background color subjectively. The observer gave a score to each of redness-greenness, blueness-yellowness and whiteness-blackness so that total score became ten. The most saturated red among the present stimuli, for example, may have been scored as 8 of red, 1 of yellow and 1 of white.

2.4 *Observers and viewing condition*

The measurement was done in a dark room and the monitor screen was viewed binocularly at 50 cm distance with natural pupils. The four observers were participated to the measurement. All observers had normal trichromats checked with the Ishihara pseudoisochromatic plates and Farnsworth-Munsell 100-Hue test.

3. Results

3.1 *Color discrimination thresholds*

The threshold distributions in the (L, M) plane for two of the observers is shown in Fig. 3. Large filled and open squares represent the background color and the open ones indicate the loci of background color where the threshold was lower than the threshold at equal energy white. Gray squares around the each large square indicate the color at the threshold to discriminate from the background color. The thresholds plotted to the directions from 45 to 180 deg were data measured with green-first test (i.e., the stimuli changed first to greenish, then to reddish). While, the thresholds plotted from 225 to 360 deg were measured with red-first test. The each threshold distributes forming two imaginary lines with positive slope. The lines were drawn passing through the origin of the (L, M) plane ($(L, M) = (0, 0)$). Since the sensitivity can be defined as the reciprocal of the threshold, the difference in the distance between the two imaginary lines (or degree of concentration of the data around the background) among background colors indicate the influence of the difference background color on the discrimination threshold (A schematic drawing was shown as Fig. 4). Figure 3 shows that color discrimination thresholds depended on the background color significantly. When the L- and M-cone luminance changed in the background color with a fixed S-cone luminance at the equal energy white, the threshold was lowest at a color near the equal energy white. The L-cone luminance of the background at the lowest threshold is slightly lower than that of the equal energy white while the M-cone luminance is slightly higher than that of the equal energy white (between 0.5 and 1 cd/m^2 in both cases). The threshold increased when the background color changed from the equal energy white. When only S-cone luminance was changed with fixed L-, M-cone luminances at the equal energy white, we found that the threshold was also lowest near the background color with the S-cone luminance of the equal energy white except for KS (Fig. 5).

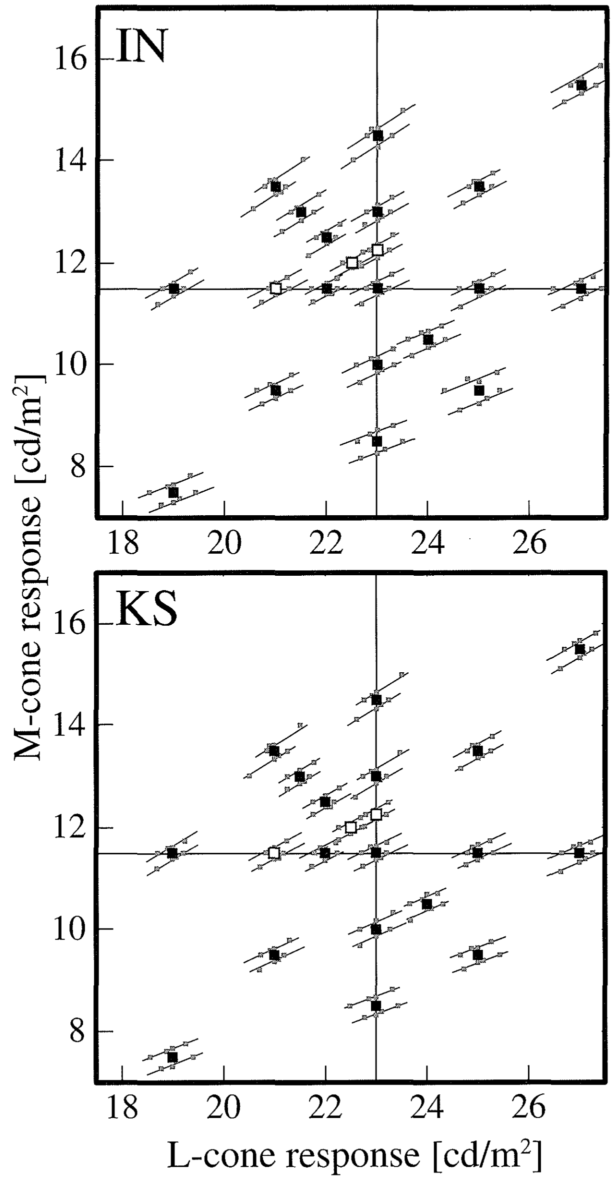

Fig. 3. The measured threshold for two observers. The results of the additional measurements were also presented in this figure (not shown in Fig. 2). Threshold distribution for each background color is represented with thin lines (See text). Large filled and open squares represent each locus of the background color and the open ones mean the background color where the threshold was lower than the threshold at the equal energy white. Small squares around each large square represent the threshold for this direction from the background color. Intersection of horizontal and vertical grid lines corresponds to the cone response at 34.5 cd/m^2 equal energy white. Note that thresholds were indicated in 1.5-fold of the actual thresholds to show the details.

3.2 *Color appearance*

Figure 6 shows the scores for whiteness in the (L, M) plane for the two observers in Fig. 3. Whiteness score was highest around the equal energy white as was the threshold. The slight difference from the equal energy white for the highest white was also similar to for the highest threshold. Slightly less L-cone luminance and more M-cone luminance was required to obtain highest whiteness score. Indeed, the equal

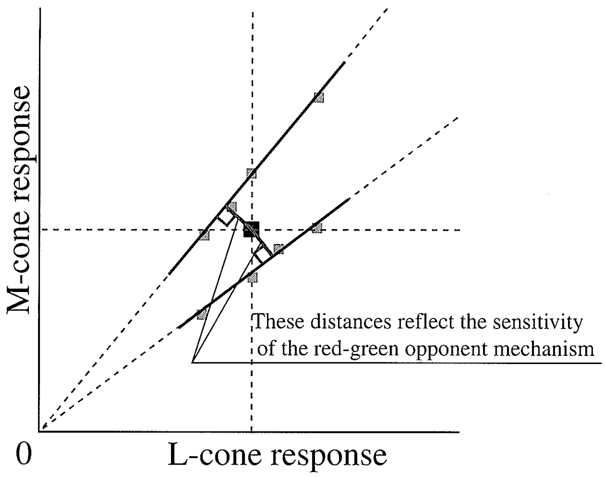

Fig. 4. Schematic draw of distribution of the thresholds and threshold contours.

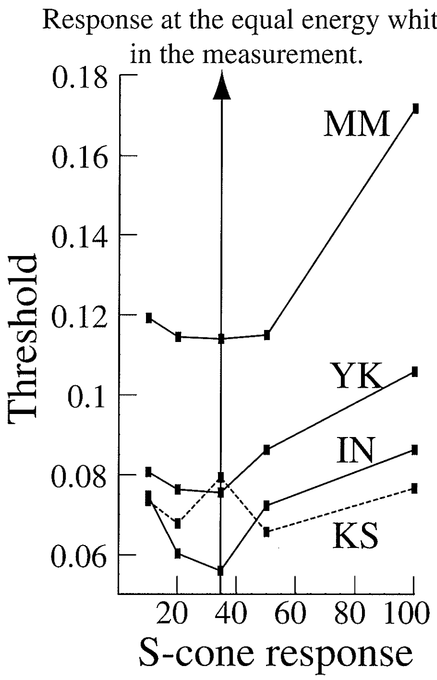

Fig. 5. Threshold in the (L, M) plane as a function of S-cone response. The S-cone response was determined to correspond to the value the amount of L- and M-cone response at equal energy white (i.e. S-cone response is 34.5 for 34.5 cd/m^2 equal energy white). The results represented by solid line mean their threshold were lowest at the equal energy white.

energy white was not unique white and small amount of redness and, yellowness or blueness was reported.

The whiteness score decreased as the increase of the distance of the background color from the point with the highest white score. The score of redness increased when L-cone luminance increased and that of greenness increased when M-cone luminance increased as shown in Fig. 7. Whiteness score decreased with the color change along the L+M line (constant L−M). This is not surprising because the luminance axis is different from the isochromatic axis, where

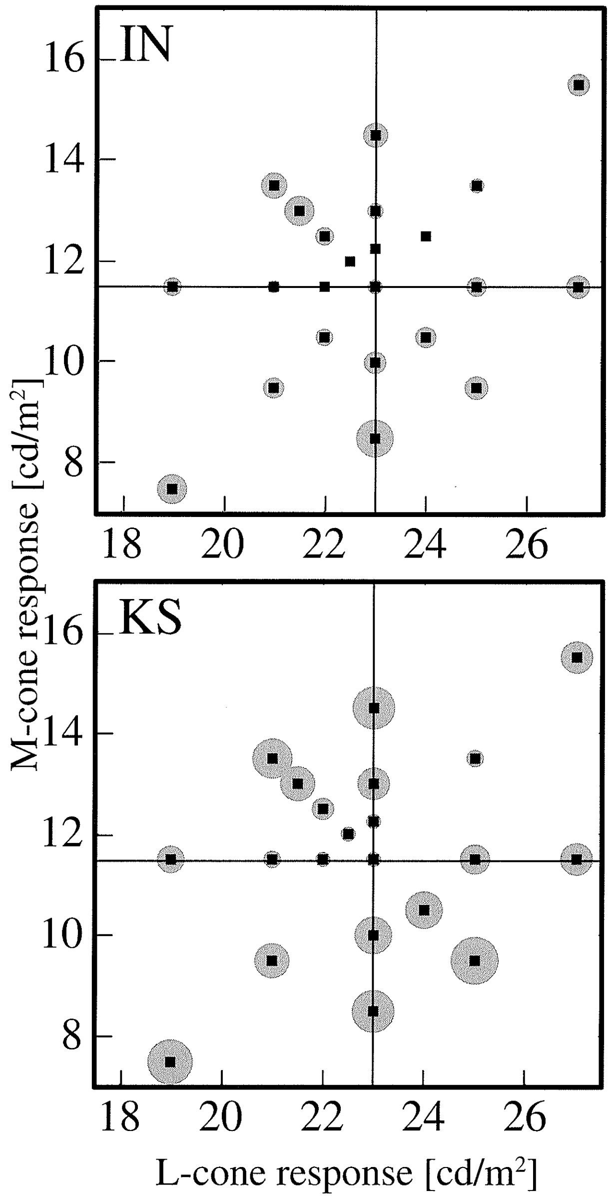

Fig. 6. The measured whiteness score for two observers. Results of the additional measurements were also presented in these figures. The diameter of the circle represents the whiteness and it was determined by (12-Whiteness score) ∗ 0.1. The score is higher as the size is smaller.

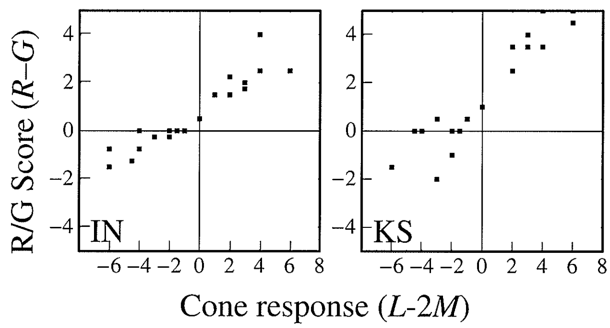

Fig. 7. Redness-greenness score ($R - G$) as a function of cone response ($L - 2M$) for two observers. Positive score means reddish perception was obtained and vice versa.

the activity ratios among three types of cones are constant. That ratio varies when the value of L+M changed with a constant value of L-M.

4. Discussion

The present measurements of color discrimination thresholds with various background (adaptation) colors provide information how the adaptation color affect to the threshold, which can be used to estimate color discriminability for specific conditions similar to our experimental ones. Moreover, the present results may be generalized by considering the underlying mechanisms for color discrimination. For the purpose, we consider the adaptation and/or nonlinear properties of the red-green opponent mechanism in this section.

It is widely accepted that the red-green opponent and luminance mechanisms contribute to the color discrimination threshold in the (L, M) plane.[3,11–13] The relative sensitivity between the red-green opponent and luminance mechanisms changes dependently on the temporal frequency of the test stimulus. The sensitivity of the red-green mechanism is higher than that of the luminance mechanism under low temporal frequency conditions. For stimuli with temporal frequencies lower than around 1 Hz, thresholds of the color change along all directions except for directions close to achromatic axis are determined by the red-green mechanism.[3,13] The red-green opponent mechanism can be modeled as the one that combines the contrasts of the input of L- and M-cone with opposite sign. If this mechanism determined threshold, the threshold distribution data should be fitted by two parallel lines with a slope of one (45 deg) in the L-, M-cone contrast, the $(\Delta L/L, \Delta M/M)$ plane. These lines are the lines which are through the origin in the (L, M) plane.

To analyze the threshold data as two parallel lines, that is, with the color opponent model in cone contrast domain, all measured thresholds were translated into the $(\Delta L/L, \Delta M/M)$ plane. The analysis showed the lines fitted to the data had a slope ranging form 0.97 to 1.04 on average for individual observer (IN: 1.04 ± 0.12 (1 S. D.), KS: 1.03 ± 0.14, MM: 1.00 ± 0.13, YK: 0.97 ± 0.17). This confirms that the thresholds obtained in the present experiment were determined by the red-green opponent mechanism. In other word, the measured thresholds reflect the characteristics of the red-green mechanism. We defined the sensitivity of the mechanism as the reciprocal of the average of the distances from the background color to the two fitted lines. Lines were fitted to the data between 45 and 180 deg and the data between 225 deg and 360 deg separately as shown in Figs. 3 and 4.

The sensitivity as a function of the L- and M-cone responses is shown in Fig. 8. The variation in luminance (i.e., L+M) cannot be identified because the two dimensional color coordinates are projected onto the $L - 2M$ line in the plot. The sensitivity was maximum when $L - 2M$ value were between -2 and 0 cd/m^2 for the all four observers. There is some contradiction about the dependence on the adaptation color of the sensitivity for red-green direction. Some studies found that the color discriminability decreased as the difference in the L- and M-cone ratio between the test color and the equal energy increases.[7,14] The threshold is minimal at the middle point of the operating range of the red-green direction.[1,6,15] On the contrary, Krauskopf *et al.*[1] reported that discrimination threshold for the red-green opponent color direction did not depend on the background color for adaptation. The different results may have been caused by the differences in the stimulus conditions such as luminance and spatiotemporal properties among different studies. Our results shows clear dependency of the discrimination threshold on the background colors, being consistent with the Boynton's[7] results although the maximum sensitivity was obtained with the color slightly different from the equal energy white. It seems that it is more common that the background influences color discriminability.

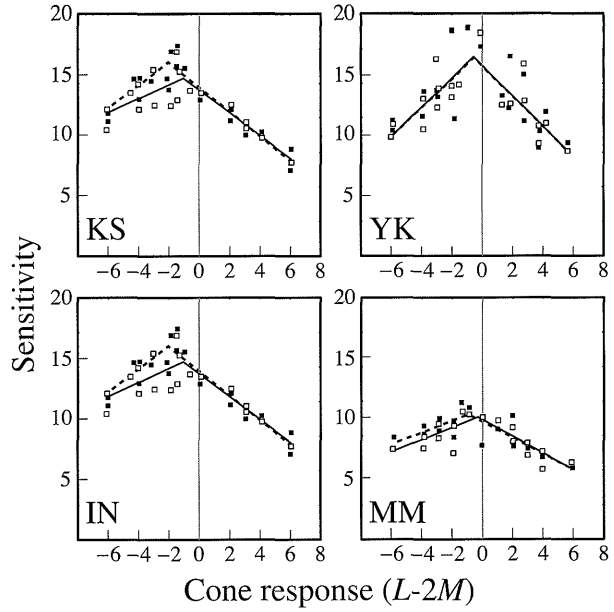

Fig. 8. Red-green opponent color $(L - M)$ mechanism sensitivity as a function of cone response $(L - 2M)$. Solid squares and solid lines represent the sensitivities measured with the green first tests while open squares and dashed lines represent measured with the red first tests. The lines were fitted by a linear regression. Since it was supposed that the maximum sensitivity was obtained around the response at equal energy white, the data for positive line fit were chosen roughly from the data with negative cone response $(L - 2M < 0)$ and vice versa.

Several studies suggest that the S-cone contributes to the red-green opponent mechanism and the perception of redness-greenness opponent color. However, whether S-cone signal increases redness (same sign of L-cone) or greenness (the same sign of M-cone) is in dispute. Stromeyer *et al.*[16] and Teuful *et al.*[17] showed that the sensitivity to detect color differences in the red-green opponent direction depends on the amount of the color change in the S-cone direction added. And the both studies estimated that S-cone contributes to the detection as if L-cone response increases by an amount ranging from 1 to 3%. On the contrary, Sankeralli *et al.*[3] estimated that S-cone contributes to the detection as if M-cone response increases by about 2%. Furthermore, Cole *et al.*[18] showed little S-cone contribution to the red-green opponent mechanism. In the present results, the sensitivity of the red-green mechanism depended on the S-cone response of the background color when L- and M-cone responses were fixed. This is consistent with the contribution of S-cone response to the red-green mechanism. The sensitivity was maximum when the S-cone response was around the equal energy white. Our result does not have any information of whether S-cone contribute to the red-green mechanism as redness or greenness since the stimulus modulated symmetrically to the background color in the (L, M) plane in our experiment. However, our result suggests that increase in S-cone response either increases or decreases the response of the red-green opponent mechanism dependently on the conditions. This may explain the inconsistent results in the literature.

A strong negative correlation between the sensitivity of the red-green mechanism and perceptual redness or greenness was shown in the present results. The sensitivity of the red-green opponent mechanism was maximum at the same response that gave the maximum whiteness (i.e. least redness and greenness). The sensitivity was low in the background conditions of saturated color. This agrees with the presumption that these second stage mechanisms, the two opponent (red-green and blue-yellow) and luminance mechanisms, determine appearances of colors and the same mechanisms also determine color discriminability.[19–21]

If the response of color opponent mechanism controls the color discrimination threshold, the present results point out an interesting issue about the adaptation states of the red-green opponent mechanism. Maximum sensitivities of the red-green opponent mechanism obtained in a quite narrow range of $L - 2M$ value: one point in the conditions used (see Fig. 8). This suggests that the adaptation of the red-green opponent mechanism is incomplete since the response of an opponent mechanism would be zero with complete adaptation. This is supported by the color appearance that also showed a narrow range of chromaticity with 100% of whiteness as Fig. 9. Although our stimulus was relatively large (6 by 6 deg in visual angle) and the total experimental duration is relatively long (about 30 min), the unique white point seemed to be stable. Although there should be significant amount of adaptation effect on the red-green opponent mechanism in our experimental conditions, the adaptation was never complete even for very unsaturated colors. Perhaps, the large stimulus field is required to obtain much larger adaptation effect.

As mentioned above, the response that gave the maximum sensitivity of the red-green mechanism in our experiment was slightly different from the other studies, which reported[2,7] that the sensitivity was maximum at the response of the equal energy white. Long-term adaptation of the red-green color perception is found in the color constancy study[20] and it may caused the differences. The difference may be related to an interesting difference about the surroundings between Japan and Western countries. The color temperatures of the illuminant and CRT monitor in Japan are set higher than Western countries. For instance, fluorescent lamp is widely used for home in Japan while incandescent lamp is preferred in Western countries. Whatever the determinant factor of the unique white point, our results indicate that the unique white point corresponds well to the point with the highest color discrimination sensitivity.

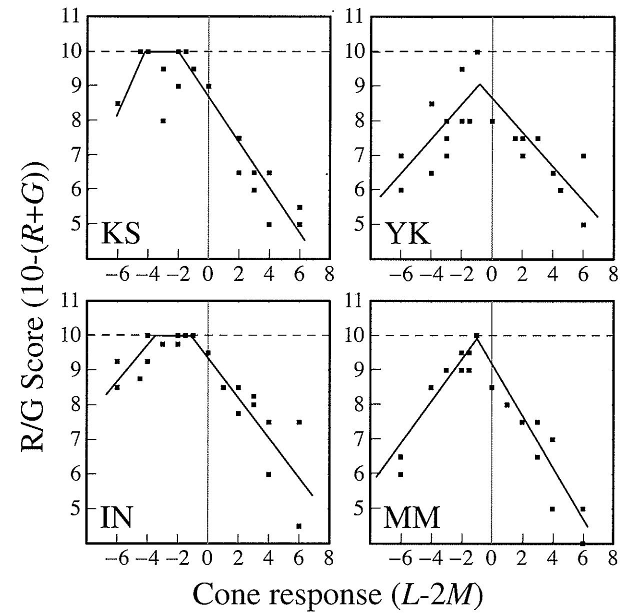

Fig. 9. Redness-greenness score $(10 - (R + G))$ as a function of cone response $(L - 2M)$. Note that the score was determined in different manner from Fig. 7. Larger score means less reddish or greenish perception was obtained. The fit was carried out by the same way as Fig. 8 except for the connecting the line with positive and negative, respectively (Data for fit were substituted whiteness score for the sensitivity). The each ends of the lines at score 10 were connected by a horizontal line since the maximum score was 10.

Macular pigment might also affect to the maximum sensitivity of the red-green mechanism. Macular pigment of human extends about four degrees on fovea and it works as an optic filter. It has been confirmed that the red-green channel does not correct the influence of the macular pigment by a psychophysical study.[23]

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